

Push-Out Bond Strength of Root Canal Sealers in Curved versus Straight Root Canals: An Invitro Research

SK Mahboob Rahaman¹, K.Sindhoori Goud², Anuradha Mukherjee³, Ankit Anand⁴, Sruti Roy⁵, Sadaf Amreen⁶

¹Assistant Professor, Department of Conservative Dentistry & Endodontics, North Bengal Dental College and Hospital, Darjeeling, West Bengal, India rskmahboob@gmail.com

²Associate Professor, Department of Conservative Dentistry & Endodontics, Malla Reddy Institute of Dental Sciences, Malla Reddy Vishwavidyapeeth, Hyderabad, Telangana, India sindhoorigoud.kodipyaka@mrsv.edu.in

³Professor and Head, Department of Conservative Dentistry & Endodontics, North Bengal Dental College and Hospital, Darjeeling, West Bengal, India mamendo2017@gmail.com

⁴Reader, Department of Conservative Dentistry & Endodontics, Mithila Minority Dental College and Hospital, Darbhanga, Bihar, India ankitanand64344@gmail.com

⁵Lecturer, Department of Conservative Dentistry & Endodontics, Government Dental College, Silchar, Assam, India srutir48@gmail.com

⁶Assistant Professor, Department of Conservative Dentistry & Endodontics, School of Dental Sciences, Sharda University, Greater Noida, Uttar Pradesh, India sadaf.amreen@sharda.ac.in
Corresponding author: SK Mahboob Rahaman, rskmahboob@gmail.com

HOW TO CITE:

SK Mahboob Rahaman, K. Sindhoori Goud, Anuradha Mukherjee, Ankit Anand, Sruti Roy, Sadaf Amreen (2026). Push-Out Bond Strength of Root Canal Sealers in Curved versus Straight Root Canals: An Invitro Research. International Journal of Special Education, 41(7s), 252-264.

COPYRIGHT STATEMENT:

Copyright: © 2026 Authors.
Open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

ABSTRACT:

Background: The success of endodontic treatment depends on effective cleaning, shaping, and obturation of the root canal system. Root canal sealers contribute significantly to the sealing ability of the obturation complex. Canal curvature may influence sealer penetration, adaptation, and adhesion to root dentin.

Aim: To compare the push-out bond strength of root canal sealers in curved and straight root canals.

Materials and Methods: Forty extracted human mandibular premolars were selected and divided into two groups according to canal morphology: straight canals (n = 20) and curved canals (n = 20). All canals were prepared using rotary nickel-titanium instruments and irrigated with sodium hypochlorite and EDTA. Specimens were obturated using gutta-percha and a bioceramic sealer. After storage at 37°C and 100% humidity for 7 days, roots were sectioned into 2-mm-thick slices. Push-out bond strength was evaluated using a universal testing machine. Data were analyzed using an independent t-test with a significance level of $p < 0.05$.

Results: The mean push-out bond strength was significantly higher in straight canals (8.42 ± 1.31 MPa) than in curved canals (6.75 ± 1.24 MPa) ($p = 0.001$). The coronal third exhibited higher bond strength values than the middle and apical thirds in both groups. Mixed and adhesive failure modes were more frequent in curved canals.

Conclusion: Canal curvature negatively affects the push-out bond strength of root canal sealers. Straight canals demonstrated superior adhesion, likely due to improved instrumentation, irrigation effectiveness, and sealer penetration.

Keywords: Bioceramic sealer, Curved canals, Endodontics, Push-out bond strength, Root canal sealer, Straight canal

Introduction:

Successful endodontic treatment depends on effective chemomechanical debridement, proper shaping of the canal space, and complete three-dimensional obturation of the root canal system. The long-term success of root canal therapy is closely associated with achieving a fluid-tight seal that prevents bacterial leakage and reinfection from the oral environment [1]. Root canal sealers play a vital role in this process by filling voids between gutta-percha and canal walls, penetrating dentinal tubules, and adapting to anatomical irregularities that cannot be sealed by core materials alone [2]. Among the various performance indicators, push-out bond strength is widely used to evaluate sealer performance, as it reflects the material's ability to adhere to dentin and resist dislodgement under functional and clinical stresses. A strong adhesive interface improves obturation stability, minimizes microleakage, and contributes to long-term treatment success [3].

Root canal anatomy is highly variable, and canal curvature represents one of the most challenging anatomical complexities in endodontics. Curved canals are frequently encountered in posterior teeth and can significantly complicate cleaning, shaping, and obturation procedures. This anatomical complexity may lead to procedural errors such as canal transportation, ledging, zipping, or insufficient debridement in certain areas of the canal system. Such difficulties can alter dentinal surface conditions and reduce the effectiveness of irrigant and sealer penetration. Consequently, canal curvature may influence both the adhesion and bond strength of root canal sealers, making it an important parameter in endodontic research and clinical evaluation [4].

Root canal sealers are used alongside core filling materials to seal accessory canals, irregularities, and microscopic spaces within the root canal system. Various types of sealers have been introduced, including zinc oxide–eugenol–based, calcium hydroxide–based, epoxy resin–based, glass ionomer–based, silicone–based, and more recently, calcium silicate–based bioceramic sealers [5]. These materials differ in composition and exhibit distinct physical, chemical, and biological properties that affect their sealing ability and adhesion to dentin [6]. Epoxy resin–based sealers, such as AH Plus, are known for their favorable flow, low shrinkage, and ability to penetrate dentinal tubules, resulting in strong adhesion. In contrast, bioceramic sealers have gained attention due to their bioactivity, hydrophilic nature, slight expansion during setting, and ability to form hydroxyapatite–like structures, which may enhance chemical bonding with dentin [7].

Bond strength is a critical property of root canal sealers, as it determines their resistance to dislodgement during functional loading, restorative procedures, and retreatment. Adequate adhesion helps maintain the integrity of the root canal filling and reduces the risk of microleakage and reinfection. Several factors influence bond strength, including the type of sealer, dentin moisture content, smear layer removal, irrigation protocol, obturation technique, and root canal anatomy. Among these, canal curvature is particularly important because it affects multiple stages of root canal treatment, including instrumentation, irrigation, and obturation, thereby influencing the final sealer–dentin interface [8]. The push-out bond strength test is a widely accepted method for evaluating sealer adhesion to root dentin. In this test, root slices are subjected to compressive force until the filling material is dislodged, and the maximum load is recorded. The

values are then converted into megapascals (MPa) based on the adhesion surface area. Compared with tensile and shear bond strength tests, the push-out method provides a more clinically relevant stress distribution and allows assessment of different root regions, including coronal, middle, and apical thirds. It also enables analysis of failure modes, which may be classified as adhesive, cohesive, or mixed, providing insight into the nature of the sealer–dentin interface [9].

Canal curvature may affect bond strength through several mechanisms. Instrumentation of curved canals is often challenging and may result in uneven dentin removal, irregular canal geometry, and incomplete smear layer removal. Additionally, irrigant penetration may be compromised, particularly in the apical region, reducing the effectiveness of smear layer elimination. These factors can limit dentinal tubule exposure and reduce sealer penetration, thereby weakening micromechanical interlocking [10]. Furthermore, obturation in curved canals is technically demanding and may lead to void formation, poor adaptation of filling materials, and non-uniform distribution of sealer along canal walls. Previous studies have demonstrated that straight canals generally exhibit higher push-out bond strength compared to curved canals. This is attributed to better access, more predictable canal shaping, and more effective irrigation, which collectively result in cleaner dentin surfaces and improved sealer adaptation. In contrast, curved canals often show reduced bond strength and a higher proportion of adhesive failures due to compromised cleaning and obturation quality. It has also been reported that the coronal third of the root consistently shows higher bond strength than the middle and apical thirds, likely due to increased dentinal tubule density and better sealer penetration in the coronal region [11]. The introduction of bioceramic sealers has opened new possibilities for improving adhesion in endodontics. These materials exhibit favorable properties such as hydrophilicity, slight expansion upon setting, bioactivity, and the ability to form mineralized interfacial layers with dentin. These characteristics may partially compensate for the challenges posed by complex canal anatomy.

However, evidence suggests that severe canal curvature may still negatively influence sealer performance due to limitations in mechanical preparation and material adaptation [12, 13]. A comprehensive understanding of the influence of canal curvature on sealer adhesion is essential for improving endodontic outcomes. Despite advances in rotary instrumentation systems, irrigation activation techniques, and obturation methods, anatomical complexity continues to be a major factor affecting treatment success. Further research is needed to evaluate the performance of contemporary sealers in different canal morphologies and to develop strategies that enhance adhesion in anatomically challenging cases. Such knowledge will assist clinicians in selecting appropriate materials and techniques, ultimately improving the predictability and longevity of root canal therapy [14]. The aim of study is to evaluate and compare the push-out bond strength of root canal sealers in straight and curved root canals. Additionally, the study aims to assess the influence of canal curvature on sealer adhesion to root dentin and the integrity of the sealer–dentin interface.

Materials and Methods

Study Design

This *in vitro* experimental study was conducted to evaluate and compare the push-out bond strength of a bioceramic root canal sealer in straight and curved root canals.

Sample Selection

Forty freshly extracted human mandibular premolars with fully formed apices and single root canals were selected for the study. Teeth with root caries, cracks, fractures, internal or external resorption, previous endodontic treatment, calcifications, or immature apices were excluded.

The teeth were cleaned of soft tissue remnants and calculus using ultrasonic scalers and stored in 0.1% thymol solution until use. Standardized digital radiographs were obtained in buccolingual and mesiodistal directions to assess canal morphology.

Grouping of Samples

Based on the degree of canal curvature determined according to Schneider's method, the specimens were divided into two groups ($n = 20$ each):

Group I (Straight Canals): Canal curvature $\leq 5^\circ$

Group II (Curved Canals): Canal curvature between 20° and 35°

Root Canal Preparation

Access cavities were prepared using round diamond burs under water cooling. A size 10 K-file was introduced into the canal until visible at the apical foramen, and the working length was established 1 mm short of this point.

Biomechanical preparation was performed using rotary nickel-titanium instruments according to the manufacturer's instructions up to size 25/0.06 taper. During instrumentation, canals were irrigated with 2.5% sodium hypochlorite solution after each instrument change.

Following completion of canal preparation, a final irrigation protocol was performed using:

5 mL of 17% EDTA for 1 minute to remove the smear layer

5 mL of 2.5% sodium hypochlorite

A final rinse with distilled water

Canals were then dried using sterile paper points.

Obturation Procedure

All root canals were obturated using a single-cone gutta-percha technique in conjunction with a premixed bioceramic root canal sealer. The master cone corresponding to the final preparation size was coated with sealer and inserted to the working length. Excess gutta-percha was removed with a heated instrument at the canal orifice and vertically compacted. The coronal access cavities were temporarily sealed with restorative material.

Storage of Specimens

The obturated teeth were stored at 37°C and 100% relative humidity for 7 days to ensure complete setting of the sealer.

Sectioning of Samples

After storage, each root was sectioned perpendicular to its long axis using a low-speed diamond saw under continuous water cooling. Three slices, each approximately 2 mm thick, were obtained from the coronal, middle, and apical thirds of the root. The thickness of each slice was verified using a digital caliper with an accuracy of 0.01 mm.

Push-Out Bond Strength Test

Each root slice was mounted on a universal testing machine. A stainless-steel plunger of appropriate diameter was positioned centrally over the filling material without contacting the surrounding dentin.

A compressive load was applied in an apico-coronal direction at a crosshead speed of 1 mm/min until dislodgement of the filling material occurred. The maximum force required for dislodgement was recorded in Newtons (N).

Push-out bond strength was calculated in MPa using the formula:

Push-out Bond Strength (MPa) = Maximum Force (N) / Adhesion Area (mm^2)

The adhesion area was calculated using the formula for the lateral surface area of a truncated cone.

Failure Mode Analysis

Following testing, the debonded specimens were examined under a stereomicroscope at $25\times$ magnification to determine the mode of failure, classified as:

Adhesive failure (between sealer and dentin)

Cohesive failure (within the sealer)

Mixed failure (combination of adhesive and cohesive)

Statistical Analysis

Data were analyzed using statistical software. Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for each group. The independent t-test was used to compare push-out bond strength between straight and curved root canals. One-way analysis of variance (ANOVA) was used to

compare bond strength among coronal, middle, and apical thirds within each group, followed by post hoc pairwise comparisons where applicable. The Chi-square test was used to compare the distribution of failure modes between straight and curved canals. A p-value of less than 0.05 was considered statistically significant.

Results:

A total of 40 extracted human mandibular premolars meeting the inclusion criteria were included in the present in vitro study. Based on

canal morphology assessed using Schneider's method, the specimens were equally distributed into two experimental groups. Group I comprised 20 teeth (50.0%) with straight root canals, while Group II consisted of 20 teeth (50.0%) with curved root canals. The equal allocation of specimens between the two groups ensured a uniform sample distribution and facilitated a reliable comparison of the push-out bond strength of the bioceramic root canal sealer between straight and curved canal configurations, as depicted in Table 1 and Figure 1.

Table 1: Distribution of Study Samples

Canal Morphology	Number of Specimens (n)	Percentage (%)
Straight Canals	20	50.0
Curved Canals	20	50.0
Total	40	100.0

■ Straight Canals ■ Curved Canals

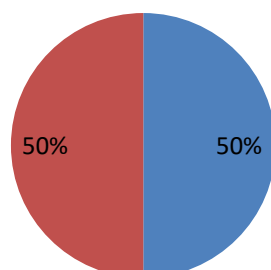


Figure 1: Graphical Representation of the Distribution of Specimens Between Straight and Curved Root Canal Groups

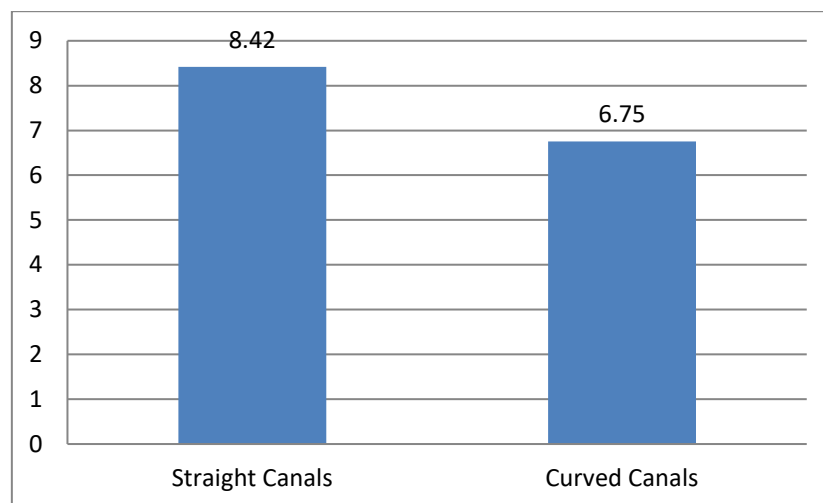
The overall push-out bond strength of the bioceramic root canal sealer was evaluated and compared between straight and curved root canals. The results demonstrated that the straight canal group exhibited a higher mean push-out bond strength (8.42 ± 1.31 MPa) compared to the curved canal group (6.75 ± 1.24 MPa). In the straight canal group, bond strength values ranged from 6.12 MPa to 10.78 MPa, whereas in the curved canal group the values ranged from 4.85 MPa to 9.18 MPa. Statistical analysis using the independent t-test revealed a statistically significant

difference between the two groups ($t = 4.12$, $p = 0.001$), indicating that canal curvature had a significant influence on the adhesion of the bioceramic sealer to root dentin. The higher bond strength observed in straight canals suggests better sealer adaptation and penetration, whereas the lower bond strength in curved canals may be attributed to the challenges associated with instrumentation, irrigation, and obturation in anatomically complex root canal systems, as depicted in Table 2 and Figure 2.

Table 2: Overall Push-Out Bond Strength of Experimental Groups

Group	n	Mean (MPa)	SD	Minimum	Maximum	t-value	p-value
Straight Canals	20	8.42	1.31	6.12	10.78	4.12	0.001*
Curved Canals	20	6.75	1.24	4.85	9.18		

*Significant at $p < 0.05$

**Figure 2:** Comparative Analysis of Push-Out Bond Strength Between Straight and Curved Root Canal Configurations

The push-out bond strength of the bioceramic root canal sealer was further evaluated at the coronal, middle, and apical thirds of the straight root canals. Among the three root levels, the coronal third exhibited the highest mean push-out bond strength (9.28 ± 1.15 MPa), followed by the middle third (8.35 ± 1.09 MPa) and the apical third

(7.63 ± 1.03 MPa). The bond strength values ranged from 7.40 to 11.40 MPa in the coronal third, 6.62 to 10.55 MPa in the middle third, and 5.95 to 9.52 MPa in the apical third. These findings indicate a gradual decrease in bond strength from the coronal to the apical region of the root canal, as depicted in Table 3.

Table 3: Push-Out Bond Strength at Different Root Levels in Straight Canals

Root Third	n	Mean (MPa)	SD	Minimum	Maximum
Coronal	20	9.28	1.15	7.40	11.40
Middle	20	8.35	1.09	6.62	10.55
Apical	20	7.63	1.03	5.95	9.52

Post-hoc analysis demonstrated statistically significant differences among all root levels. The coronal third showed significantly higher bond strength than the middle third, with a mean difference of 0.93 MPa ($p = 0.014$). Similarly, the coronal third exhibited significantly greater bond strength compared with the apical third, with a mean difference of 1.65 MPa ($p < 0.001$).

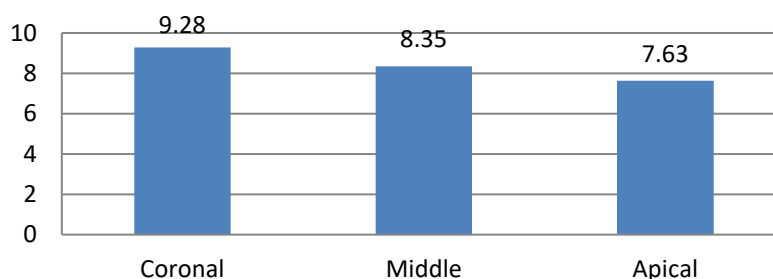
Furthermore, the middle third demonstrated significantly higher bond strength than the apical third, with a mean difference of 0.72 MPa ($p = 0.041$). These results suggest that the adhesion of the bioceramic sealer was most effective in the coronal region and progressively decreased toward the apical region of the root canal, as depicted in Table 4.

Table 4: Post-Hoc Comparison of Root Levels in Straight Canals

Comparison	Mean Difference	p-value	Significance
Coronal vs Middle	0.93	0.014*	Significant
Coronal vs Apical	1.65	<0.001*	Significant
Middle vs Apical	0.72	0.041*	Significant

The superior bond strength observed in the coronal third may be attributed to the greater density and diameter of dentinal tubules, improved accessibility for instrumentation and irrigation, and enhanced sealer penetration into dentinal tubules. In contrast, the apical third exhibited the lowest bond strength values, possibly due to reduced tubule density, limited irrigant penetration, and the

anatomical constraints associated with the apical region. Overall, the findings indicate that root level significantly influences the push-out bond strength of the bioceramic sealer in straight root canals, with the coronal third providing the most favorable conditions for sealer adhesion, as depicted in Figure 3.

**Figure 3:** Mean Push-Out Bond Strength of the Bioceramic Root Canal Sealer in the Coronal, Middle, and Apical Thirds of Straight Root Canals

The push-out bond strength of the bioceramic root canal sealer was assessed at the coronal, middle, and apical thirds of the curved root canals. The results revealed that the coronal third demonstrated the highest mean push-out bond strength (7.54 ± 1.06 MPa), followed by the middle third (6.68 ± 0.98 MPa), while the apical third exhibited the lowest mean bond strength ($6.03 \pm$

0.92 MPa). The recorded bond strength values ranged from 5.84 to 9.65 MPa in the coronal third, 5.12 to 8.78 MPa in the middle third, and 4.61 to 7.92 MPa in the apical third. A progressive reduction in bond strength from the coronal to the apical region was observed, indicating that root canal level significantly influenced sealer adhesion in curved canals, as depicted in Table 5.

Table 5: Push-Out Bond Strength at Different Root Levels in Curved Canals

Root Third	n	Mean (MPa)	SD	Minimum	Maximum
Coronal	20	7.54	1.06	5.84	9.65
Middle	20	6.68	0.98	5.12	8.78
Apical	20	6.03	0.92	4.61	7.92

Post-hoc analysis demonstrated statistically significant differences between all root levels. The coronal third exhibited significantly greater bond strength than the middle third, with a mean difference of 0.86 MPa ($p = 0.021$). Likewise, the bond strength in the coronal third was significantly higher than that in the apical third, showing a

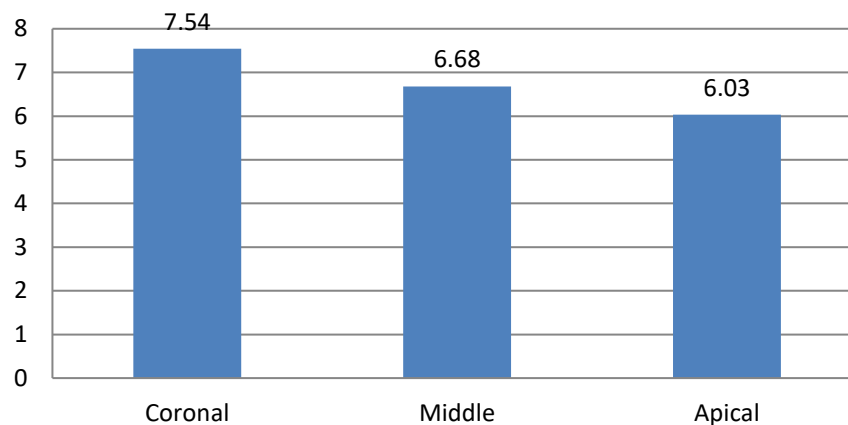
mean difference of 1.51 MPa ($p < 0.001$). Furthermore, the middle third demonstrated significantly higher bond strength than the apical third, with a mean difference of 0.65 MPa ($p = 0.048$). These findings indicate that sealer adhesion decreased significantly toward the apical portion of the canal, as depicted in Table 6.

Table 6: Post-Hoc Comparison of Root Levels in Curved Canals

Comparison	Mean Difference	p-value	Significance
Coronal vs Middle	0.86	0.021*	Significant
Coronal vs Apical	1.51	<0.001*	Significant
Middle vs Apical	0.65	0.048*	Significant

The higher bond strength values observed in the coronal third may be attributed to improved accessibility for instrumentation and irrigation, more effective smear layer removal, and a greater density of dentinal tubules that facilitate sealer penetration and micromechanical retention. Conversely, the lower bond strength observed in the apical third may be related to the anatomical challenges associated with curved canals, including restricted irrigant penetration, limited dentin

surface conditioning, and reduced sealer adaptation. Overall, the results suggest that canal curvature adversely affects sealer bonding throughout the root canal system, with the apical region being the most susceptible to reduced adhesion. These findings highlight the importance of meticulous cleaning, shaping, and obturation techniques when managing curved root canals to achieve optimal sealing ability and long-term endodontic success, as depicted in Figure 4.

**Figure 4:** Comparison of Mean Push-Out Bond Strength of the Bioceramic Root Canal Sealer at Different Root Levels in Curved Root Canals

The push-out bond strength of the bioceramic root canal sealer was compared between straight and curved canals at the coronal, middle, and apical root thirds. The results demonstrated that straight canals exhibited significantly higher bond strength values than curved canals at all evaluated root levels.

At the coronal third, the mean push-out bond strength was 9.28 ± 1.15 MPa in straight canals and 7.54 ± 1.06 MPa in curved canals. The difference between the two groups was highly statistically significant ($t = 4.95$, $p < 0.001$), indicating superior sealer adhesion in straight canals. Similarly, in the middle third, straight canals showed significantly higher mean bond strength

(8.35 ± 1.09 MPa) compared to curved canals (6.68 ± 0.98 MPa). Statistical analysis revealed a highly significant difference between the groups ($t = 5.08$, $p < 0.001$).

In the apical third, the lowest bond strength values were observed in both groups. Nevertheless, straight canals continued to demonstrate significantly greater bond strength (7.63 ± 1.03 MPa) than curved canals (6.03 ± 0.92 MPa). The intergroup difference was highly significant ($t = 5.22$, $p < 0.001$). Notably, the greatest difference between the two canal configurations was observed in the apical third, suggesting that canal curvature exerts a more pronounced negative effect on sealer adhesion in the apical region.

Overall, the findings indicate that root canal curvature significantly reduces the push-out bond strength of the bioceramic sealer throughout the root canal system. Straight canals consistently demonstrated superior bond strength at the coronal, middle, and apical thirds when compared with curved canals. The reduced bond strength observed in curved canals may be attributed to

difficulties in canal instrumentation, limited irrigant penetration, incomplete smear layer removal, and compromised sealer adaptation associated with complex canal anatomy. These results emphasize the influence of canal morphology on the quality of the sealer–dentin interface and the long-term stability of root canal obturation, as depicted in Table 7 & Figure 5.

Table 7: Intergroup Comparison of Push-Out Bond Strength of Bioceramic Root Canal Sealer at Different Root Levels in Straight and Curved Canals

Root Third	Straight Canals (Mean $\pm$ SD)	Curved Canals (Mean $\pm$ SD)	t-value	p-value
Coronal	9.28 $\pm$ 1.15	7.54 $\pm$ 1.06	4.95	<0.001*
Middle	8.35 $\pm$ 1.09	6.68 $\pm$ 0.98	5.08	<0.001*
Apical	7.63 $\pm$ 1.03	6.03 $\pm$ 0.92	5.22	<0.001*

*Statistically significant ($p < 0.05$)

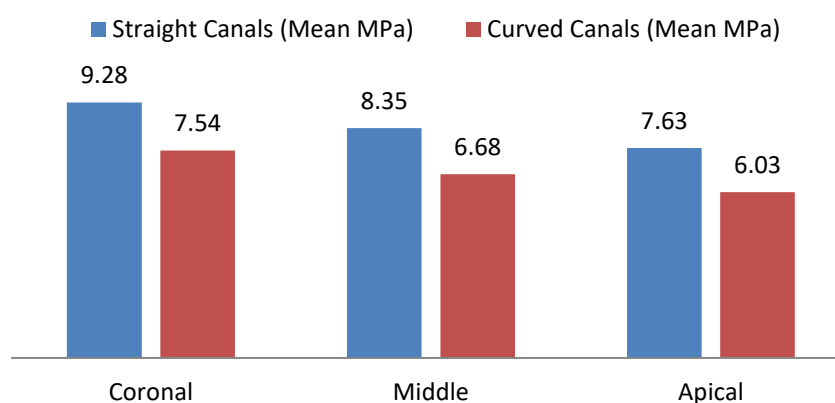


Figure 5: Comparison of Mean Push-Out Bond Strength Between Straight and Curved Root Canals at Coronal, Middle, and Apical Thirds

The distribution of failure modes following the push-out bond strength test was evaluated and compared between the straight and curved canal groups. Three types of failure patterns were observed, namely adhesive, cohesive, and mixed failures. Mixed failure was the most frequently encountered mode in both groups, accounting for 56.7% of specimens in straight canals and 46.7% in curved canals. Cohesive failure was observed in 30.0% of specimens in the straight canal group and 20.0% in the curved canal group.

A notable difference was observed in the incidence of adhesive failures, which occurred more frequently in curved canals (33.3%) compared with straight canals (13.3%). Adhesive failure represents

debonding at the sealer–dentin interface and is generally indicative of weaker adhesion between the root canal sealer and dentinal walls. The higher proportion of adhesive failures in curved canals suggests that canal curvature negatively affected the quality of bonding and adaptation of the bioceramic sealer to root dentin.

Statistical analysis using the Chi-square test demonstrated a significant difference in the distribution of failure modes between the two groups ($\chi^2 = 7.863$, $p = 0.023$). This finding indicates that root canal morphology significantly influenced the pattern of bond failure. The predominance of mixed failures in both groups reflects satisfactory interaction between the sealer

and dentin; however, the increased occurrence of adhesive failures in curved canals supports the bond strength findings and further confirms that canal curvature adversely affects sealer adhesion.

Overall, straight canals exhibited more favorable failure characteristics, whereas curved canals

showed a greater tendency toward adhesive debonding, suggesting compromised integrity of the sealer–dentin interface in anatomically complex canal system, as depicted in Table 8 & Figure 6.

Table 8: Comparison of Failure Modes Between Groups

Failure Mode	Straight Canal n (%)	Curved Canal n (%)	Chi Square value	P value
Adhesive	8 (13.3)	20 (33.3)	7.863	0.023
Cohesive	18 (30.0)	12 (20.0)		
Mixed	34 (56.7)	28 (46.7)		

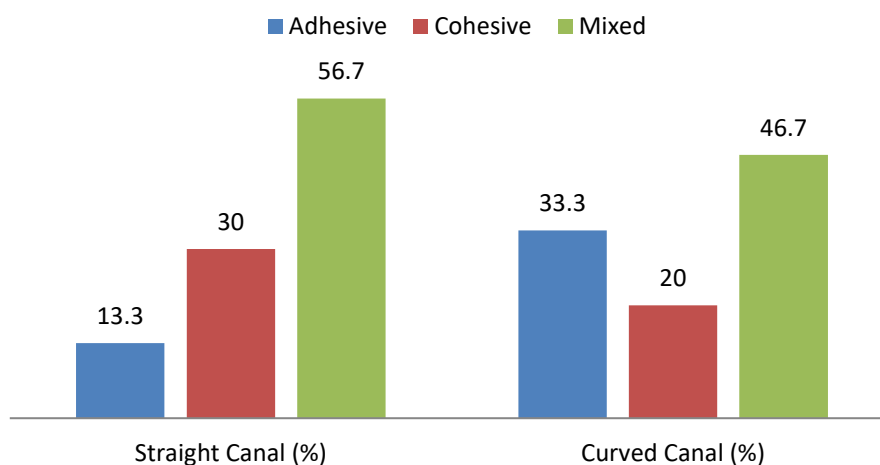


Figure 6: Distribution of Adhesive, Cohesive, and Mixed Failure Modes in Straight and Curved Root Canal Groups

Discussion

The present in vitro study evaluated the influence of root canal curvature on the push-out bond strength of a bioceramic root canal sealer. The results demonstrated significantly higher bond strength values in straight canals compared with curved canals, leading to the rejection of the null hypothesis. These findings suggest that canal curvature adversely affects the adhesion of root canal sealers to dentin and may compromise the integrity of the sealer–dentin interface.

The superior bond strength observed in straight canals may be attributed to more effective instrumentation and irrigation procedures. Schilder (1974) emphasized that the complexity of root canal anatomy, particularly canal curvature,

presents challenges during cleaning and shaping procedures [6]. Curved canals often restrict instrument contact with canal walls, resulting in uneven dentin preparation and incomplete removal of the smear layer. Neelakantan et al. (2011) reported that dentin surface conditioning and smear layer removal significantly influence sealer adhesion and push-out bond strength. Therefore, the reduced bond strength observed in curved canals may be related to the persistence of debris and smear layer, which can interfere with sealer penetration and bonding [11].

Another explanation for the lower bond strength values in curved canals is the difficulty in achieving uniform sealer distribution throughout the root canal system. Lee et al. (2002) demonstrated that effective adhesion of root canal sealers depends on

intimate contact with dentin and penetration into dentinal tubules. In curved canals, anatomical irregularities may hinder sealer flow and reduce dentinal tubule penetration, particularly in the apical region. Such limitations can weaken both micromechanical interlocking and chemical interaction between the sealer and dentin, resulting in reduced resistance to dislodgement [2].

The present study also revealed that the coronal third exhibited higher push-out bond strength than the middle and apical thirds, regardless of canal configuration. These findings are in agreement with those reported by Cimpean et al. (2022), who observed greater bond strength values in the coronal region due to increased dentinal tubule density and improved sealer penetration. The apical third contains fewer and narrower dentinal tubules, limiting the ability of sealers to penetrate and establish a strong bond. Furthermore, irrigation effectiveness decreases toward the apical region because of restricted access and reduced irrigant exchange, which may negatively affect dentin cleanliness and bonding [12].

Failure mode analysis demonstrated a higher incidence of adhesive and mixed failures in curved canals. Adhesive failures indicate disruption at the sealer–dentin interface and suggest inadequate bonding between the sealer and root dentin. Similar observations have been reported by Nagas et al. (2009), who found that factors affecting sealer adaptation and penetration can significantly influence bond strength and failure patterns. The greater frequency of adhesive failures in curved canals further supports the notion that anatomical complexity compromises sealer adhesion [5].

The favorable overall performance of the bioceramic sealer in both groups may be explained by its physicochemical properties. According to Raghavendra et al. (2017), bioceramic sealers are characterized by hydrophilicity, dimensional stability, biocompatibility, and bioactivity [8]. More recently, Prasad Kumara et al. (2025) highlighted the ability of these materials to form hydroxyapatite and establish a mineral infiltration zone at the sealer–dentin interface, enhancing bonding and sealing ability. These properties may

account for the satisfactory bond strength values obtained in the present study. Nevertheless, despite their bioactive nature, bioceramic sealers were unable to completely overcome the adverse effects of canal curvature on adhesion.

The findings of this study are clinically relevant because successful root canal obturation depends on maintaining a durable seal that prevents microleakage and reinfection. Ørstavik (2005) emphasized that the quality of obturation materials and their adaptation to canal walls are critical determinants of long-term endodontic success [1]. The reduced bond strength observed in curved canals suggests that clinicians should pay particular attention to irrigation, canal preparation, and obturation procedures when managing anatomically complex root canals. To improve bonding in curved canals, enhanced irrigation strategies and advanced instrumentation techniques may be beneficial. Activation methods such as passive ultrasonic irrigation, sonic agitation, and negative-pressure irrigation systems have been shown to improve irrigant penetration and smear layer removal in difficult-to-reach areas. Similarly, the use of flexible nickel–titanium instruments may facilitate more effective preparation while preserving canal anatomy. Careful obturation techniques designed to optimize sealer distribution and minimize void formation may further improve the integrity of the sealer–dentin interface in curved canals [151].

Limitations & Future Directions of the Study

This study has several limitations that should be considered when interpreting the results. First, the investigation was conducted under in vitro conditions, which cannot completely replicate the complex biological and mechanical environment of the oral cavity. Factors such as periodontal ligament simulation, occlusal forces, temperature fluctuations, and long-term aging were not reproduced. Second, only one type of root canal sealer (bioceramic sealer) was evaluated. Therefore, the findings may not be generalizable to other sealer formulations, such as epoxy resin-based, zinc oxide eugenol-based, or calcium hydroxide-based sealers. Third, the sample size was relatively

small and limited to extracted human mandibular premolars. Variations in dentin structure, canal anatomy, and degree of curvature among teeth may have influenced the results despite standardization efforts. Fourth, the study assessed bond strength after a short storage period of seven days. Long-term performance, durability of adhesion, and resistance to degradation over time were not evaluated. Finally, only the push-out bond strength test was used to assess sealer adhesion. Other important properties, including sealer penetration depth, microleakage resistance, interfacial adaptation, and volumetric stability, were not investigated. Future studies incorporating different sealer types, larger sample sizes, advanced imaging techniques, and long-term aging protocols are recommended to provide a more comprehensive understanding of the influence of canal curvature on sealer performance.

Conclusion

Within the limitations of this in vitro study, root canal curvature significantly influenced the push-out bond strength of the tested bioceramic sealer. Straight root canals demonstrated higher bond strength values compared with curved root canals, indicating superior sealer adhesion to dentin. In both groups, the coronal third exhibited greater bond strength than the middle and apical thirds. The reduced adhesion observed in curved canals may be attributed to challenges in instrumentation, irrigation, and sealer penetration. Clinicians should consider the influence of canal morphology when selecting obturation materials and techniques to achieve optimal long-term sealing of the root canal system.

References

- ØRSTAVIK, D. (2005), Materials used for root canal obturation: technical, biological and clinical testing. *Endodontic Topics*, 12: 25-38. <https://doi.org/10.1111/j.1601-1546.2005.00197.x>
- Lee KW, Williams MC, Camps JJ, Pashley DH. Adhesion of endodontic sealers to dentin and gutta-percha. *J Endod*. 2002 Oct;28(10):684-8. doi: 10.1097/00004770-200210000-00002. PMID: 12398164.
- Mastoras K, Vasiliadis L, Koulaouzidou E, Gogos C. Evaluation of push-out bond strength of two endodontic post systems. *J Endod*. 2012 Apr; 38(4):510-4. doi: 10.1016/j.joen.2011.12.039. Epub 2012 Jan 29. PMID: 22414839.
- Gomes-Filho JE, Gomes BP, Zaia AA, Ferraz CR, Souza-Filho FJ. Evaluation of the biocompatibility of root canal sealers using subcutaneous implants. *J Appl Oral Sci*. 2007 Jun; 15(3):186-94. doi: 10.1590/s1678-77572007000300007. PMID: 19089128; PMCID: PMC4327465.
- Nagas E, Altundasar E, Serper A. The effect of master point taper on bond strength and apical sealing ability of different root canal sealers. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2009 Jan; 107(1):e61-4. doi: 10.1016/j.tripleo.2008.09.020. PMID: 19101485.
- Schilder H. Cleaning and shaping the root canal. *Dent Clin North Am*. 1974 Apr; 18(2):269-96. PMID: 4522570.
- Zhang H, Shen Y, Ruse ND, Haapasalo M. Antibacterial activity of endodontic sealers by modified direct contact test against *Enterococcus faecalis*. *J Endod*. 2009 Jul; 35(7):1051-5. doi: 10.1016/j.joen.2009.04.022. PMID: 19567333.
- Raghavendra SS, Jadhav GR, Gathani KM, Kotadia P. Bioceramics in endodontics - a review. *J Istanbul Univ Fac Dent*. 2017 Dec 2; 51(3 Suppl 1):S128-S137. doi: 10.17096/jiufd.63659. PMID: 29354316; PMCID: PMC5750835.
- Wang JS, Bai W, Wang Y, Liang YH. Effect of different dentin moisture on the push-out strength of bioceramic root canal sealer. *J Dent Sci*. 2023 Jan; 18(1):129-134. doi: 10.1016/j.jds.2022.06.025. Epub 2022 Jul 12. PMID: 36643254; PMCID: PMC9831826.
- Kuriakose F, Joy B, Mathew J, Karathodiyil R, R H, Philip T. The Effects of Various Final Irrigants on the Bond Strength of Root Dentin Exposed to Chloroform: An In vitro Study. *J Pharm Bioallied Sci*. 2021 Jun; 13(Suppl 1):S629-S632. doi: 10.4103/jpbs.JPBS_555_20. Epub 2021 Jun 5. PMID: 34447168; PMCID: PMC8375833.

- Neelakantan P, Subbarao C, Subbarao CV, De-Deus G, Zehnder M. The impact of root dentine conditioning on sealing ability and push-out bond strength of an epoxy resin root canal sealer. *Int Endod J*. 2011 Jun; 44(6):491-8. doi: 10.1111/j.1365-2591.2010.01848.x. Epub 2011 Jan 24. PMID: 21255047.
- Cimpean SI, Burtea ALC, Chiorean RS, Dudescu MC, Antoniac A, Robu A, Campian RS, Timis LI. Evaluation of Bond Strength of Four Different Root Canal Sealers. *Materials (Basel)*. 2022 Jul 17; 15(14):4966. doi: 10.3390/ma15144966. PMID: 35888436; PMCID: PMC9321937.
- Prasad Kumara PAAS, Cooper PR, Cathro P, Gould M, Dias G, Ratnayake J. Bioceramics in Endodontics: Limitations and Future Innovations-A Review. *Dent J (Basel)*. 2025 Apr 1; 13(4):157. doi: 10.3390/dj13040157. PMID: 40277487; PMCID: PMC12026347.
- Martín-González J, Echevarría-Pérez M, Sánchez-Domínguez B, Tarilonte-Delgado ML, Castellanos-Cosano L, López-Frías FJ, Segura-Egea JJ. Influence of root canal instrumentation and obturation techniques on intra-operative pain during endodontic therapy. *Med Oral Patol Oral Cir Bucal*. 2012 Sep 1; 17(5):e912-8. doi: 10.4317/medoral.18234. PMID: 22549694; PMCID: PMC3482542.
- Giachetti L, Scaminaci Russo D, Baldini M, Bertini F, Steier L, Ferrari M. Push-out strength of translucent fibre posts cemented using a dual-curing technique or a light-curing self-adhering material. *Int Endod J*. 2012 Mar; 45(3):249-56. doi: 10.1111/j.1365-2591.2011.01969.x. Epub 2011 Oct 19. PMID: 22007679.